ANZICE: Antarctica-NZ Climate Extremes

Overview and Policy Implications of the ANZICE Research Programme

Antarctic Research Centre – March 2010

Report prepared for the ANZICE Programme by Sean Weaver
of Carbon Partnership Ltd.

Dr Sean Weaver, Principal, Carbon Partnership Ltd.
81 Severn St, Island Bay, Wellington. Ph +64 4 383 6898,
email: sean.weaver@carbon-partnership.com
Web: www.carbon-partnership.com

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The ANZICE Research Program

The **A**ntarctica**-N**ew **Z**ealand **I**nterglacial **E**xtreme **C**limates (**ANZICE**) research programme is an initiative of the Antarctic Research Centre at Victoria University of Wellington. The goal of the ANZICE programme is to help determine past and future effects of global warming on the Antarctic, Southern Ocean and New Zealand region. This derives from our current understanding of the special relationship Antarctica has in driving significant components of New Zealand's as well as the world's climate and oceans. This understanding will assist in the development of New Zealand climate change adaptation strategies and policies.

The research focuses on detailed reconstructions of past warm climatic extremes in Antarctica, the Southern Ocean and as far as north as New Zealand (e.g. detailed examinations of conditions in previous warm cycles when temperatures 1-3 °C warmer than now and hence are viable analogues for the future). The research programme is driven by two basic questions:

1. "How will Antarctica respond to a warmer world? *and*
2. What are the contemporary effects on the southern ocean and climate?"

These questions are being addressed by 3 research programmes:

A. Antarctic Climate Drivers will identify Antarctica's behaviour under warm past extremes especially relating to the atmosphere, sea-ice and ice shelf dynamics.
B. Southern Ocean-NZ Responses will determine ocean and land responses in New Zealand to climate changes in Antarctica.
C. Models and Policy will provide a predictive capability to the ice-ocean-climate research and its linkages to policy concerning environmental management now and into the future.

This report presents the resource material for the first stage of the Policy component of the work stream C. This material encompasses the policy-relevant aspects emerging from the ANZICE research.

The Science / Policy Interface

The purpose of publicly funded climate science is to generate reliable knowledge that can be used by society to make decisions concerning our relationship with the climate system. This includes

a. increasing our knowledge of the climate system and human interactions with this system (scientific basis),
b. helping to understand the nature, scale, and timing of climate change risk (vulnerability),
c. helping to develop realistic climate change adaptation goals and strategies (adaptation), *and*
d. helping the formulation of realistic climate change mitigation goals and strategies (mitigation).

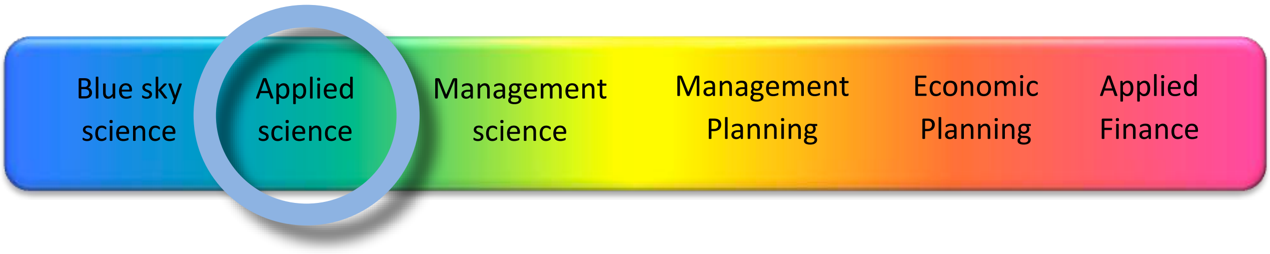
For society to make use of science in its policy decisions there needs to be compatibility between the science and policy communities. This compatibility increases when both communities better understand each other's needs, capabilities, and constraints, and when information shared between these communities is communicated in a form that is accessible to each. There is therefore an important role for translation of meanings and priorities across the science/policy interface in a two-way fashion. The role of the ANZICE policy component is to help translate the relevance of the ANZICE research findings to a policy audience.

For science to be used in the public policy process it needs to be accurate, reliable and up-to-date, but also accessible to those whose role is to consume this information and usefully apply it. In terms of accuracy and reliability, the scientific community has developed a quality assurance process designed to safeguard the production of accurate and reliable knowledge. This quality assurance arises from a combination of the scientific method, the peer review process, and building scientific consensus concerning new additions to the corpus of accepted knowledge.

The development of a corpus of accepted scientific knowledge comes about by consensus building in the science community. This process is being actively supported by the United Nations due to the importance of accurate and reliable climate science for policy makers. The United Nations Framework Convention on Climate Change developed a scientific advisory body to provide policy-relevant (but not policy-prescriptive) climate change science. This international advisory body is known as the Intergovernmental Panel on Climate Change (IPCC).

The role of the IPCC is to provide accurate, reliable, and up-to-date scientific knowledge to the global climate policy community, by means of a cyclical (approximately 6 year) comprehensive review of published scientific research results. This review process is also designed to generate scientific consensus on key areas of policy-relevant climate science. This consensus is important for the policy community to have confidence in the scientific information they need to use to make decisions.

The translation of science into policy runs along a spectrum from pure science to applied finance. Between these ends of the spectrum is a range of intermediary steps:



The research findings provided by ANZICE can fit into this spectrum at the "Applied Science" end of this spectrum. This research also fits into the overall process of the IPCC by generating high quality scientific results published in peer reviewed scientific literature, which in turn will be subject to the cyclical review process undertaken by the IPCC.

One approach for ANZICE to the delivery of science to the policy community would be to simply generate high quality scientific papers and let the IPCC review and synthesis process do the rest. This would be sufficient to generate accurate, reliable and up-to-date scientific information that in time may become incorporated into the corpus of accepted scientific knowledge, and then used by the policy community.

ANZICE has chosen to be more proactive in its efforts to provide not only high quality science for the IPCC process, but also translate this science into a form that is more accessible to the policy community. The key is to ensure that quality is not lost in translation.

The first step in the translation process is to locate ANZICE science in the broader context of climate science and its service to the policy community as framed by the IPCC working groups. The IPCC developed three broad categories of scientific knowledge for purposes of assisting the process of science-based policy development. These categories are:

1. Scientific Basis (understanding of the Earth system)
2. Impacts, Vulnerability and Adaptation (identifying current and likely future impacts of trends in the Earth system on human systems)
3. Mitigation (determining what can be done to change the human drivers of climate change)

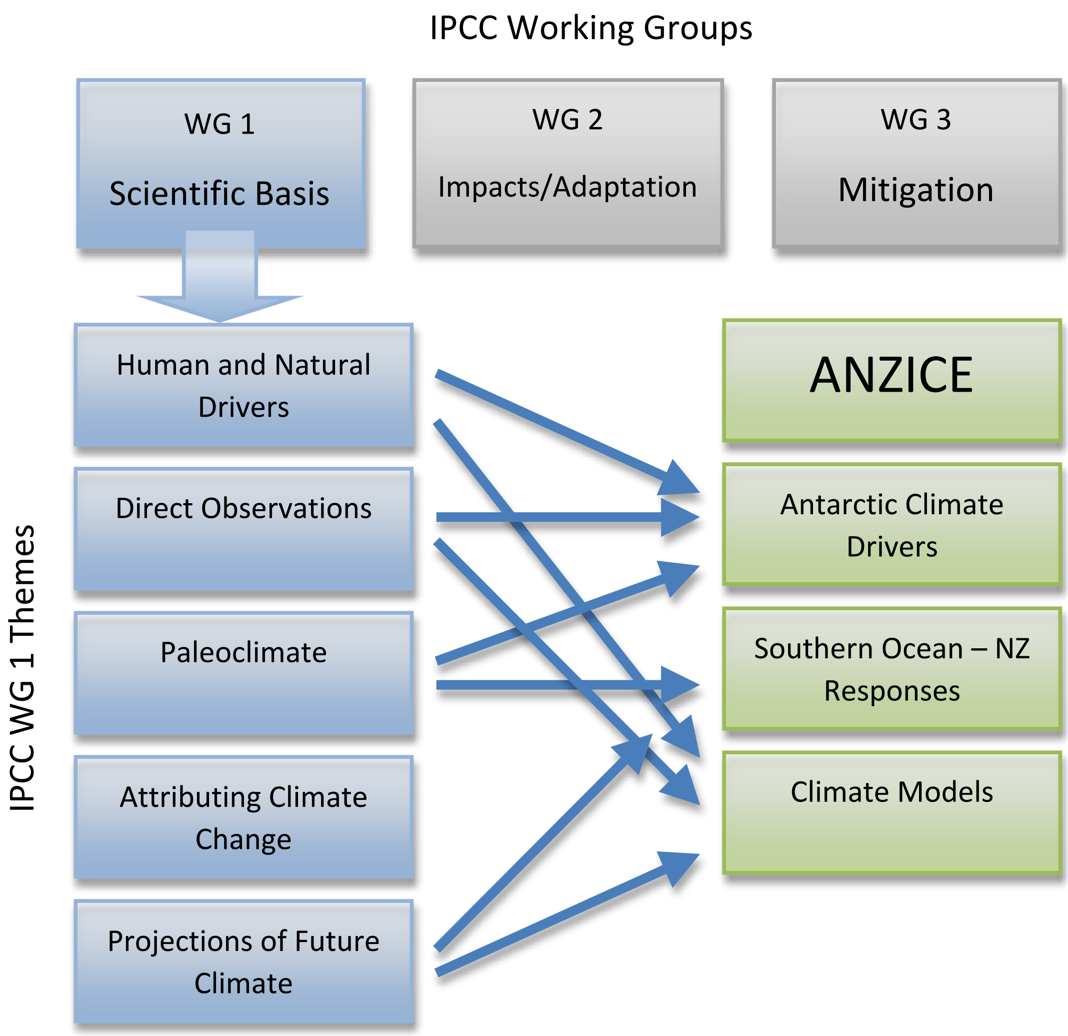


Figure 1. ANZICE Relationship to IPCC Working Groups

ANZICE research fits within the IPCC Working Group 1 framework with a strong emphasis on paleoclimate research and Earth system interactions.

ANZICE research is positioned at the cutting edge of natural system science, and designed to help improve our overall knowledge of currently poorly understood components of the climate/ocean/cryosphere system. This is part of an international scientific effort to provide a robust foundation for societal responses to climate change, by strengthening international knowledge of the climate system but in ways that are particularly relevant to Southern Hemisphere, Southern Ocean, and Antarctic dynamics.

The relevance of this knowledge to New Zealand relates to the influence that the Southern Ocean and Antarctica has on the New Zealand environment. For example, much of New Zealand climate and weather patterns are strongly influenced by southern polar as well as tropical weather systems.

This research also has global relevance. For example, Antarctic ice sheet dynamics have an influence on global sea levels and the better we can assess these dynamics, the better we can understand the scientific basis of sea level rise.

Antarctic Climate Drivers

The Antarctic Climate Drivers group is led by Dr Nancy Bertler and focuses on high resolution ice core data from Antarctica. As snow accumulates year after year on glaciers and the ice sheets of Antarctica, the snow and ice layers can be read like pages in a detailed diary of past environmental conditions. These carefully collected and frozen archives contain information about the past temperature, humidity, snow accumulation, atmospheric circulation, atmospheric concentration of greenhouse gases and pollutants, storminess, seasonality, sea-ice extent, and production of ocean plankton.

Figure 2. Ice core from the ANZICE drilling programme.

The ANZICE team collects cores (Fig.2) from coastal sites in Antarctica. These sites have been chosen because they are particularly good in recording information on changes in the ocean/climate system. Coastal regions in Antarctica have orders of magnitude more snow accumulation than the desert like Antarctic interior. This is equivalent to adding more pages to a dairy, which allows scientists to reconstruct the past conditions in detail. Sometimes, even monthly accuracy for hundreds to thousands of years into the past can be achieved. Scientists consult the past climate history as a guide to the cause of current climate change through the identification of natural versus human-influenced signal, and as a guide to Antarctica's response to warmer climes.

IS ANTARCTICA WARMING OR COOLING?

There are only about five weather stations in Antarctica that recorded local climate for more than 50 years. Since then, the network of weather stations has expanded. However, it is only since the 1970s with the improvement of satellite measurements, that scientists know daily temperatures right across the continent. Unfortunately, this time period also coincides with when carbon dioxide from the burning of fossil fuels and production of other green house gasses appear to cause global warming. If we would like to know what the natural climate of Antarctica was like, we can measure the composition of the atmosphere directly by analysing the gas bubbles trapped in ice and indirectly through the use of proxies. These proxies are properties that scientists measure on the ice cores to produce a readable diary of climate history. From these measurements, we know for example, that Antarctica is very sensitive to changes in the tropics, governed by the El Nino Southern Oscillation, or ENSO. Every 3-7 years, the tropical Western Pacific experiences warmer than usual sea-surface temperatures, which we call an El Nino event. This is associated with a large re-organisation of ocean currents and winds that

affect much of the whole world, including New Zealand and Antarctica. In the Ross Sea Region, an El Nino event carries warmer surface ocean waters to the Antarctic that arrive there within about 3 months of leaving the tropical Pacific. In addition, it shifts the Amundsen Sea Low, a semi permanent low pressure system, from its normal position in the Ross Sea to the coast of Marie Byrd Land.

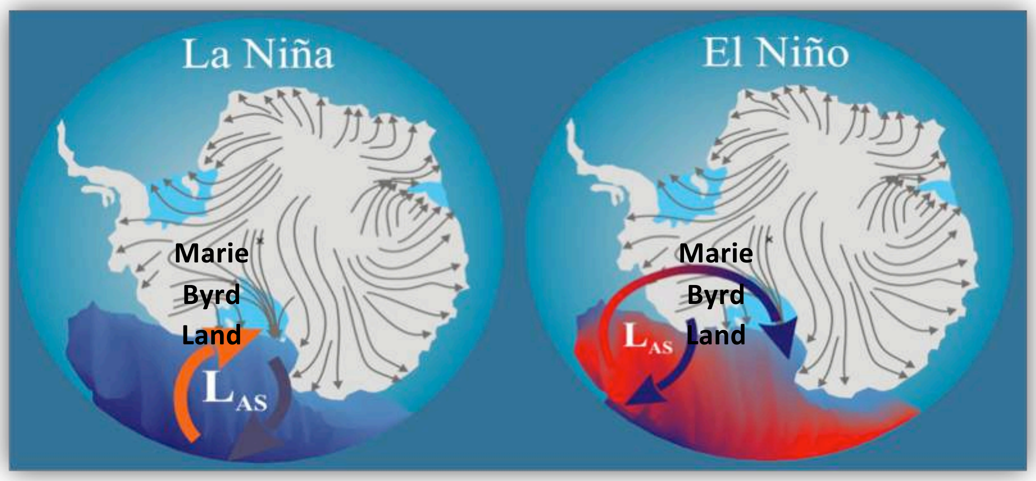


Figure 3. Influence of ENSO on Antarctica. Shift in Amundsen Sea Low (L_{AS}) causing indirect cooling in western Ross Sea during El Nino events.

The ANZICE team uses ice cores to show that during such El Nino events, the Ross Sea is dominated by air masses that descend from West Antarctica (Fig. 3), and are therefore cold. The opposite is true for La Nina events. Here the tropical Pacific experiences upwelling of particularly cold waters, which cool Antarctica's Southern Ocean within 3 months of leaving the tropics. This causes the Amundsen Sea Low to shift north of the Ross Sea, bringing warmer, marine air masses into the region. At Scott Base, the New Zealand base at the northern tip of the Ross Ice Shelf, Antarctica, this means that during El Nino years the summers are colder than La Nina years. Since 1977 we have experienced an unusually high number of strong El Nino events. This explains why the Ross Sea region experienced a cooling rather than a warming during this time (Bertler et al. 2004, 2006). This shows the importance of obtaining long enough records of past climate variability to provide a baseline to measure change against and also to understand the mechanisms of the climate system. When all measurements from Antarctica are taken into account, scientists have found that over the past 50 years, all of Antarctica has been warming. In particular West Antarctica and the Ross Sea experience rapid and substantial warming (Steig et al., 2009, Fig.4)

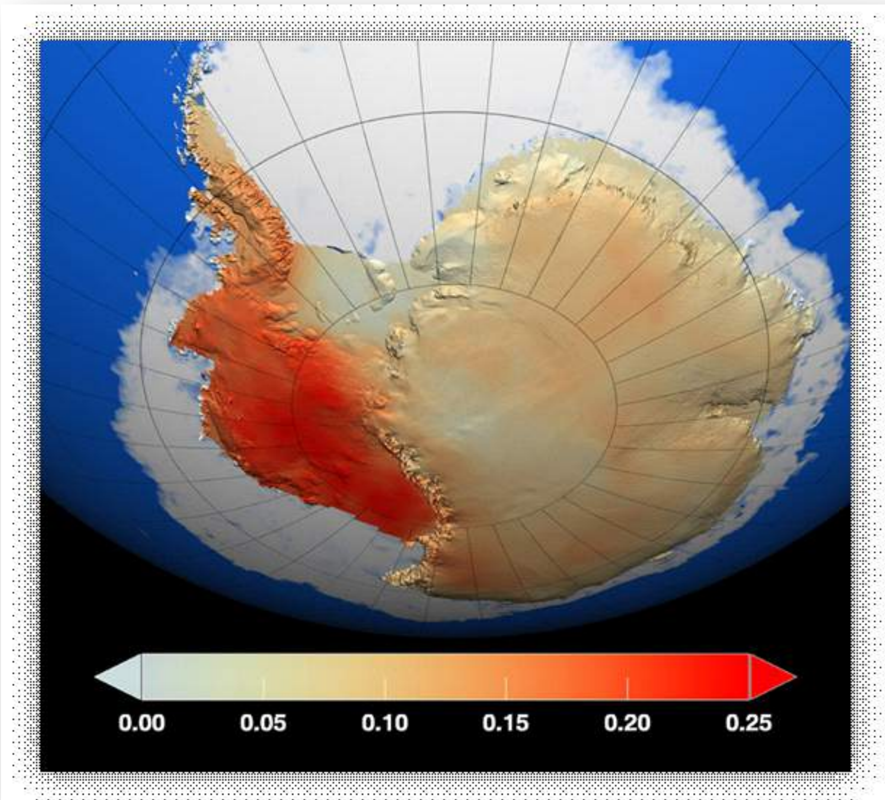


Figure 4. Antarctic Warming over last 50 years. Red represents areas where temperatures have increased the most during the last 50 years (0.25 °C each decade for a total warming of 1.25 °C), particularly in West Antarctica and the Ross Ice Shelf, while white colours indicate no temperature change or a very slight cooling. Temperature changes are measured in degrees Celsius. Credit: NASA/GSFC Scientific Visualization Studio.

WHAT ARE THE IMPACTS OF A WARMER ANTARCTICA ON THE NZ CLIMATE AND THE OCEAN?

As Antarctica warms, its influence on the ocean and atmosphere changes with implications for New Zealand and the rest of the world.

Ocean Temperatures

A detailed study of ocean temperatures using historical records and more recently small devices that float with currents and transmit ocean temperature and salt content via satellite to laboratories around the world, show that the Southern Ocean has warmed (Böning et al., 2008). Scientists are concerned in particular as this warming trend, while small, can be measured to depths of 1,000m and deeper, thereby creating a vast store of heat (Böning et al., 2008). A warmer Southern Ocean will experience less extensive sea-ice coverage and reduced sea ice

coverage is likely to cause more warming, as sea ice is an efficient reflector of solar energy back into space. As open-ocean replaces white sea-ice, more of the suns energy is absorbed by the ocean, which in turn further warms the ocean and warmer oceans melt more sea-ice in a feedback cycle.

The formation of sea-ice is a critical driver of the ocean thermohaline circulation, which moves vast amounts of heat, gases and nutrients around the Earth. The world's largest current, the Antarctic Circumpolar Current (ACC) flows past southern New Zealand bringing cold water to the region. Thus the ACC influences climate and the production of marine plankton as the cold Antarctic waters meet the warm subtropical waters at about the latitude of Christchurch. Below 2000m water depth, the circumpolar current taps off a deep flow into the Pacific Ocean that is the largest arm of the global thermohaline current system.

Ice Shelf Collapse and Sea Level Increase

Warmer ocean and atmospheric temperatures are thought to be a cause of recently observed collapses of ice shelves in the Antarctic Peninsula. In the past 30 years, we have seen an unprecedented partial destruction or total disintegration of ten ice shelves (Alley et al., 2005). While the loss of ice shelves does not cause sea-level to rise, the shelves serve as a barrier for glaciers and ice sheets. Once the barrier is lost, the land-grounded ice accelerates into the ocean, which increases global sea-level (Scambos et al., 2004). The largest ice shelf in the world, the Ross Ice Shelf, is a natural barrier for the West Antarctic Ice Sheet. A total collapse of the West Antarctic Ice Sheet has the potential to raise global sea-level by up to 5m (Vaughan and Spouge, 2002). The ANZICE team is one of many international groups, including the NZ led-ANDRILL Programme, that are concerned about the stability of the Ross Ice Shelf and the West Antarctic Ice Sheet. The ANZICE team plans to recover a 780m deep ice core from Roosevelt Island, which will provide information on how quickly the Ross Ice Shelf retreated from it's northern most extent during the last glacial period (about 30,000 years ago) to its current extent during much warmer conditions. From this, scientists hope to calculate at which temperature the ice shelf would collapse.

Mass Balance and Sea-Level Increase

The mass balance of an ice sheet is determined by whether the amount of snow that is deposited onto the ice sheet each year is balanced by an equal amount lost at it's margin, due to melt or carving of ice. If the ice sheet receives more snow fall than it looses ice, scientists speak of a positive mass balance, and the ice sheet as growing. If the ice sheet looses more mass than it receives, through melt and calving, the mass balance is negative and the ice sheet shrinks. Measuring the mass balance of Antarctica is very difficult, as on average the vast interior only accumulates about 3cm of ice per year (i.e. the interior is almost a desert in terms of annual precipitation). However, only a small change in the mass balance has substantial effects on sea-level. For example a 1% change in the mass balance of Antarctica equals 0.7m of global sea-level change. The ANZICE team monitors mass balance at coastal locations. This is important as these sites are particularly sensitive to ocean and atmospheric temperature changes and these areas are particularly difficult to measure with satellite data due to the steep topography at the margin.

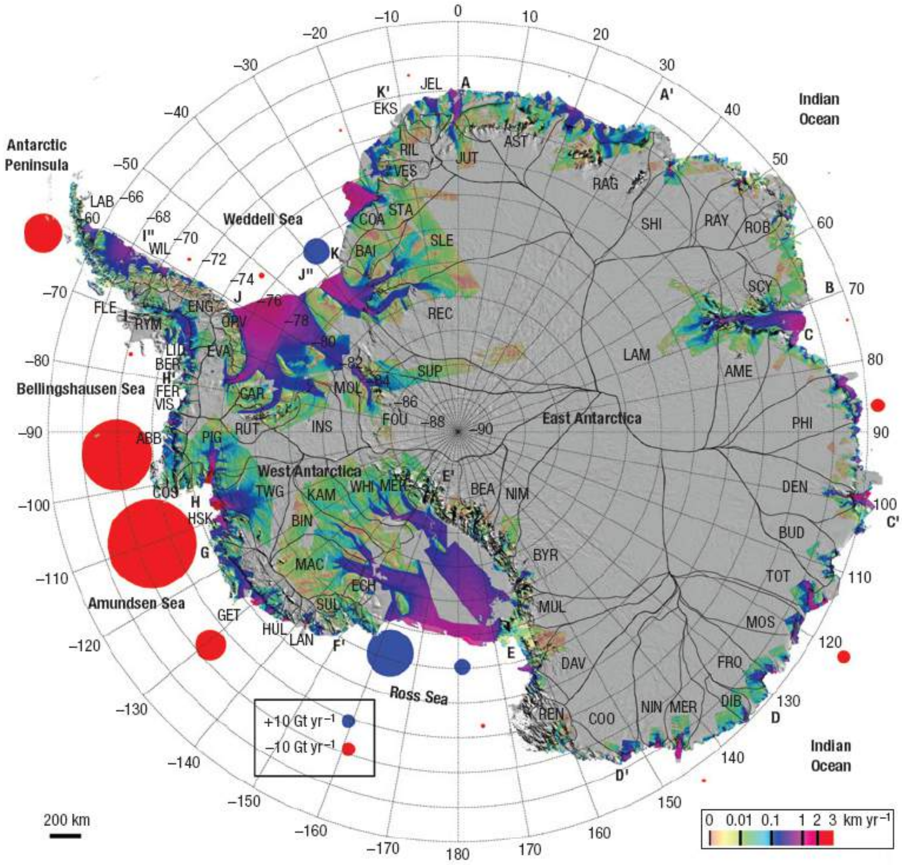


Figure 5: Mass Balance of the Antarctic continent. Red colours indicate negative mass balance, blue colour positive mass balance. The size of the circles is indicative of the amount of change. Source: Rignot et al., 2009, Nature.

In Figure 5, Rignot et al. (Nature, 2009) used satellite data to show that a substantial part of West Antarctica is losing mass to the ocean (red dots). They also note that the Ross Sea is currently experiencing a positive mass balance (blue dots), indicating that the ice sheet in this region is growing. However, ANZICE accumulation data show that along the coastal region of the Trans-Antarctic Mountains, snow accumulation shows a strong decrease over the past 40 years, which could soon lead to negative mass balance in this area too.

POLICY IMPLICATIONS

The research results arising from the Antarctic Climate Drivers team have several implications for climate policy. Perhaps the most important consequence of the Ross Sea ocean-atmosphere research (from a policy point of view) is that it helps explain the system dynamics of the Antarctic climate, and how this can generate anomalies such as regional cooling against a backdrop of continental and global warming. Thus it is essential to understand that climate does not warm in a steady manner and that it does vary in time and place, but the overall warming trend is upward.

The ANZICE research in Antarctica can play an important role in helping to provide high quality, independent scientific explanations for policy makers who seek to understand and interpret

sometimes conflicting messages concerning climate trends in Antarctica. The ANZICE findings together with the results coming from other research programs in Antarctica help to explain the uneven distribution of temperature changes under a warming climate.

Providing such explanations is an important aspect of helping bridge the gap between science and society, and aligns with the efforts of the NZ Royal Society Climate Committee to provide independent answers to frequently asked questions concerning the climate system.

Southern Ocean – New Zealand Responses

Oceans cover about 71% of the Earth and contain about 90% of its biomass. At the top of the marine food chain is the fishing industry. At the bottom of this food chain is plankton, which falls into two broad categories – 1. zooplankton (animals) which feed on 2. phytoplankton (plants). Many forms of single celled plankton have skeletal structures that upon death sink to the ocean floor carrying with them chemical indicators of the ocean in which they lived. By detailed analysis of these microscopic fossils preserved in and taken from marine sediment cores, we can provide a history of past ocean and climatic conditions with remarkable accuracy. This is essentially the forensic science of past climate change.

Warmer ocean temperatures in past climates have been associated with high concentrations of plant plankton in ocean waters (e.g. algal blooms). For example, the warm Cretaceous seas (65-145 million years ago) accumulated large volumes of sediment made of the skeletal structures of plant plankton. These sediments eventually became chalk – an example of which is the White Cliffs of Dover in England.

Over the coming centuries, global surface (air) and ocean (water) temperatures are projected to increase and this may influence algal growth, with potential consequences for those that rely on marine ecosystems. The IPCC includes the likely increase of algal blooms in their assessment of future impacts of global warming (Parry et al., 2007) Algal blooms have become more frequent and geographically widespread in recent decades (see Fig. 6),(Anderson, 1989).

Figure 6. Milky swirls in the ocean east of Banks Peninsula are coccolith algal blooms.

Source: NASA visibleearth.nasa.gov/view_rec.php?id=1304.

Marine algal blooms have implications for human and marine ecosystem health, because some algal species produce harmful toxins. By the year 2000, marine toxins arising from algal blooms

were responsible for over 60,000 human intoxication incidents per year, with a 1.5% mortality rate. Algal blooms are also responsible for extensive die-offs of fish, shellfish, birds and marine mammals, and other animals dependent on the marine food web (Van Dolah, 2000).

It is unclear whether temperature is the most important driver of algal productivity or whether other factors such as nutrients, sunlight, or structure of the surface ocean play supporting or even dominant roles.

ALGAL BLOOMS PAST AND PRESENT

The Southern Ocean research group are determining past climate interactions with the ocean system using marine sediment cores from the ocean floor. One of the questions driving this research is how marine algae have responded to past interglacial warm periods, which unlike the present warming phase occur on a predictable cycle that is determined by Earths inclination and path around the sun. This research is designed to help us understand what we might expect from the influence of global warming on the Southern Ocean of New Zealand.

By understanding the environmental preferences and tolerances of contemporary marine plant and animal plankton, we can then interpret past ocean conditions from the relative abundance of these species in the distant past. For example, an abundance of polar species off New Zealand indicates ice age or glacial conditions. In addition, the shells of the plankton carry chemical signatures that help unravel past ocean temperatures, nutrients in the sea water, slat content, ocean fertility and even the amount of ice tied up in the poles during the ice ages.

PLANKTON AND TEMPERATURE

Sediment core research has focussed on Foraminifera or forams. Forams are amoeba-like organisms with a shell made of calcium carbonate. These shells sink to the seabed and become incorporated into ocean floor sediments. In warm climates plant plankton (mostly coccolithophores) can dominate the sediment layers (see Fig. 7). Analyzing the relative proportions of forams to coccolithophores in sediment cores can reveal patterns that can be compared with other variables like past temperatures, salinity and solar radiation.

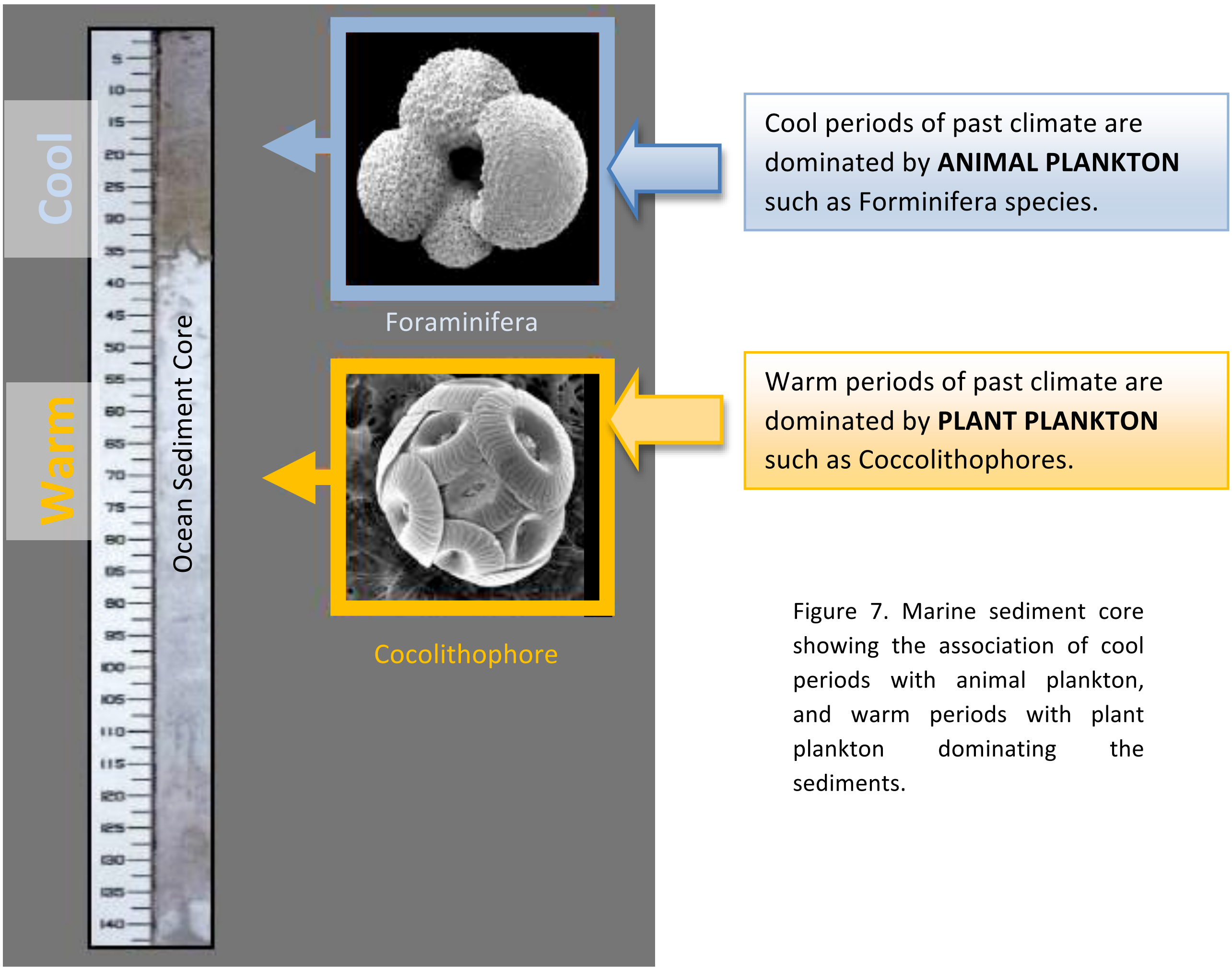


Figure 7. Marine sediment core showing the association of cool periods with animal plankton, and warm periods with plant plankton dominating the sediments.

Dr Gavin Dunbar and students Annette Bolton and Bella Duncan are conducting research on sediment core samples taken from the north and east of New Zealand. By measuring the particle size distribution in samples from these cores, the ANZICE researchers hope to reconstruct how the relative abundances of coccolithophores and foraminifera change over time.

ALGAE AND SOLAR RADIATION

Algal blooms are known to be influenced by a combination of factors including temperature, solar radiation, ocean structure and dissolved nutrients. The key for this component of ANZICE research is to determine which of these factors is the main driver of algal bloom activity.

Nutrient concentration in surface waters is thought to be influenced by ocean mixing and upwelling of nutrient-rich waters from the deeper ocean (below the zone where photosynthesis takes place) where nutrients go unused. Warm climate periods tend to be associated with increased solar heating, lower wind speeds and as a consequence, less mixing of the different

layers in the water column. Cold periods on the other hand tend to involve more frequent winds and higher wind speeds, which increase mixing.

This pattern of more mixing of ocean waters in colder climates and more upwelling of deep ocean nutrients does not correspond very closely with the evidence of more frequent algal blooms during warm periods. Accordingly, the answer may lie elsewhere. One possibility is the role of solar radiation, perhaps in combination with temperature. An interesting pattern that is emerging from the ANZICE research shows a possible correlation between high algae concentrations and high solar radiation in past climates.

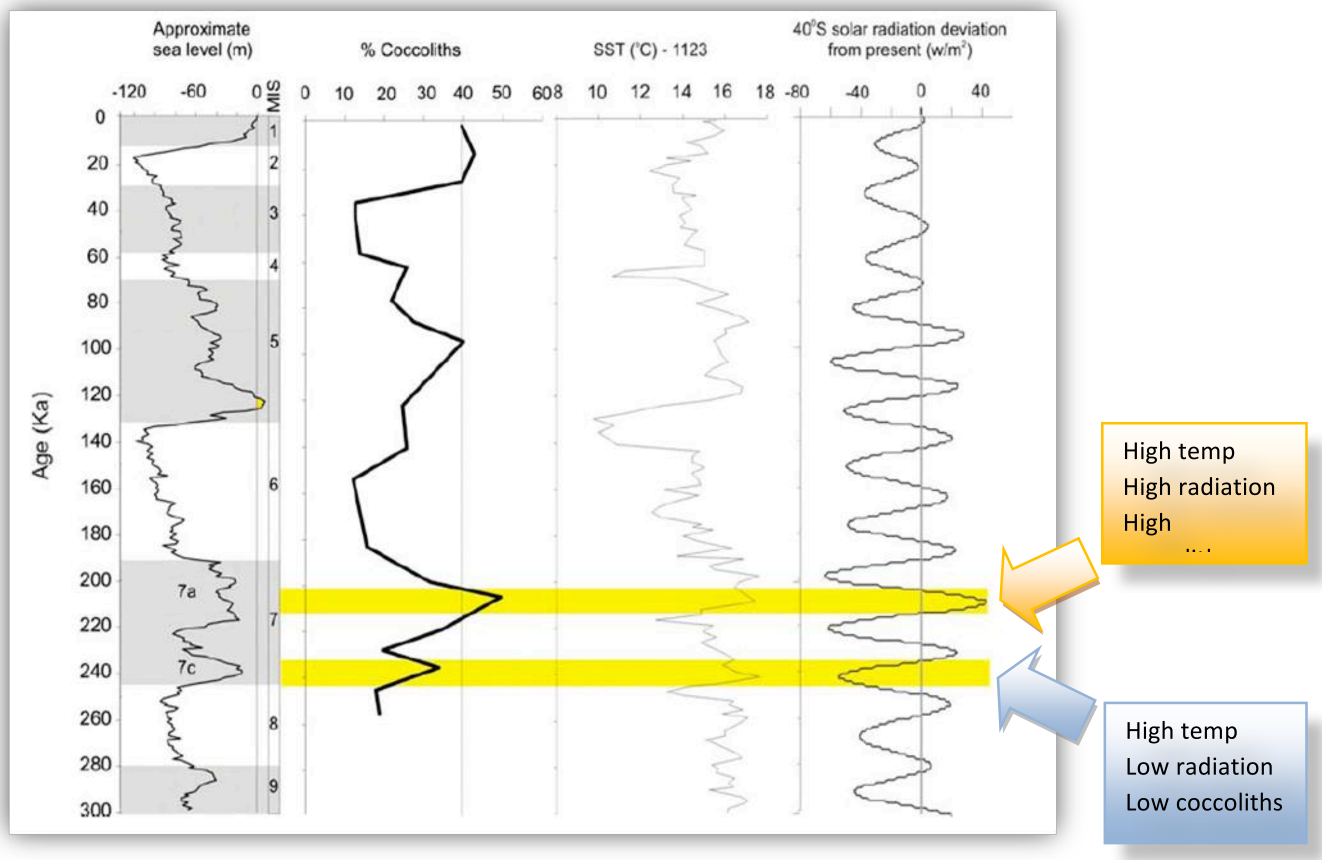


Figure 8. Record of coccolithophore abundance in comparison with solar radiation over the last 300,000 years.

As can be seen in Figure 8, there is an alignment and possible correlation between high concentrations of coccolithophores and high solar radiation. Of particular interest to the ANZICE team is a close approximation to a "controlled experiment" provided by the history preserved in the core. This approximate "controlled experiment" comes in the form of two periods with similar ocean temperatures (210,000 years ago and 240,000 years ago shown in the yellow bands in Fig. 8). One of these periods (210,000 years ago) coincides with high ocean temperatures, high southern hemisphere solar radiation and high coccolithophore concentrations. This contrasts with 240,000 years ago where similarly high ocean temperatures coincide with low solar radiation, and lower concentrations of coccolithophores.

POLICY IMPLICATIONS

The policy relevance of this research relates to our knowledge of poorly known systems and the implications of change in these systems for resource management, now and into the future as the climate warms. Algal blooms already have a significant effect on inshore waters, especially where aquaculture activities are taking place. Our understanding of likely future impacts of a warming climate on the frequency and intensity of algal blooms will be an important factor in better managing the New Zealand fisheries sector.

Climate Models

Climate models represent different components of the climate system using mathematical language. They can simulate the dynamic interactions between two or more components (e.g. the atmosphere, oceans, ice, land, and the biosphere). Models are essentially encyclopaedias of what we know and a means of testing that knowledge. Such model simulations can be tested for accuracy against historical data and then used to help form projections of climate change phenomena into the future.

The policy community is interested in making resource management and economic decisions based on a clear understanding of the climate system and the likely future changes. The climate modelling work of the ANZICE team is designed to help us better assess future projections for two components of the climate system: Antarctic ice shelves and temperate glaciers of New Zealand's Southern Alps.

ICE SHELVES

Ice shelves are the floating extensions of land-based glaciers and ice sheets that evolve in response to climatic cycles especially the glacial (ice age) to interglacial (warm age) cycles. Recent dramatic losses of long-lived ice shelves in both hemispheres have highlighted the uniqueness of recent warming and focused attention on causal factors that promote shelf collapse.

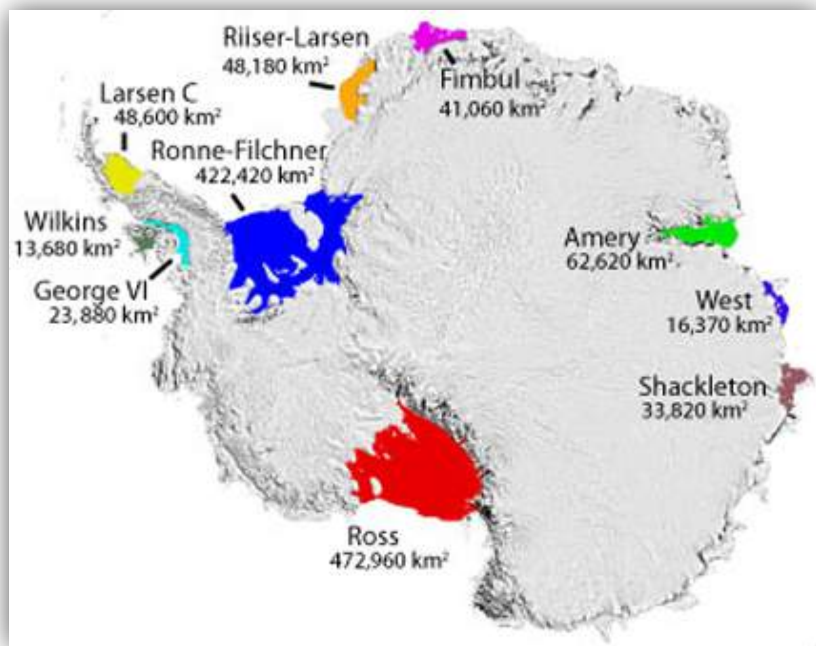


Figure 9. Major ice shelves in Antarctica (Scambos et al., 2007).

On the Antarctic Peninsula the Larsen B ice shelf (Fig. 10) collapsed in 2002 – an event unprecedented in the last 10,000 years. This came after at least a decade of thinning and melting at its base. This ice shelf collapse has been widely attributed to warm surface air temperatures which led to the development of surface melt ponds and ice fracturing.

Figure 10. Larsen B Ice Shelf Collapse, 2002.

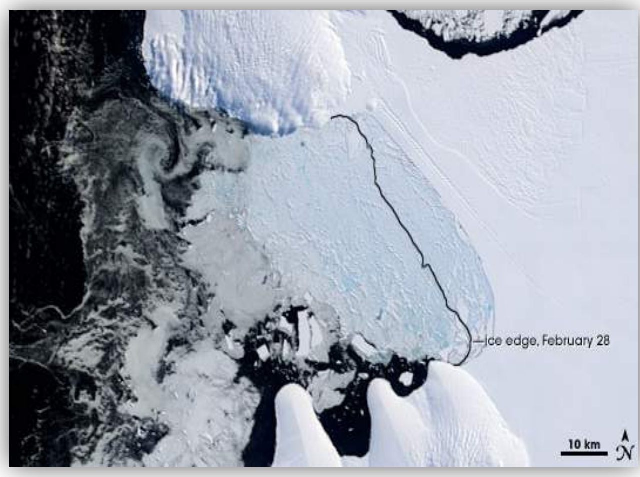


Figure 11. Wilkins Ice Shelf collapse, March 2008.

The Wilkins ice shelf (Fig. 11), which undergoes extensive summer melt ponding, also experienced a break up in 2007/2008.

A similar process has been observed on northern Ellesmere Island in Canada, where the Ward Hunt ice shelf collapsed between 2002 and 2008, and the Ayles ice shelf collapsed in 2005.

These ice shelf collapses occurred in close association with warm surface air temperatures (SAT), widespread melt pond formation and melting by the ocean that circulates beneath the shelves.

The ANZICE work on Antarctic ice shelves is exploring their stability in a warming world. A recently developed model involving the ice-ocean-atmosphere has been linked to a three dimensional ice flow model in an attempt to better understand the way ice shelves respond to a warmer atmosphere. When the model was tested against past ice shelf collapses, it successfully reproduced the historically recorded demise of ice shelves on the Antarctic Peninsula and in the Canadian Arctic. This demonstrated the accuracy of the model and confirmed its potential to be used to generate reliable projections of future ice shelf stability.

Ice shelves become unstable when melt water forms ponds on their surface. This water may seep down cracks in the ice and refreeze. The refreezing ice expands and drives the cracks even wider. Through repetition of this freeze/thaw process a point is reached where the shelf becomes disrupted with fissures that promote structural weakness and failure. Melt water ponds form when there is persistently warm summer SAT. One way of calculating the extent of ice and snow melt for a particular period is the positive degree-day (PDD) method. The melting point for snow and ice is proportional to the total number of positive degree-days or days above the melting point of snow and ice. An earlier study of the northern hemisphere ice shelves found that an ice sheet needed less than 200 positive degree days per year to remain stable (Copland et al., 2007). This 200 PDD threshold was used in the ANZICE ice shelf model.

The ANZICE team developed conservative model that burns all the available fossil carbon and then looks at the stability of ice shelves in Antarctica and in the Arctic. The model estimates that

such fossil fuel burning would lead to a 7°C warming globally by 2700. In association with this warming comes increased instability of ice shelves.

The model describes ice shelf stability for three time periods (1850, 2050, and 2800) in the Antarctic and Arctic regions. During the preindustrial climate (1850), the Arctic shows large regions of ice shelf stability (see Fig. 12), and the entire Antarctic continent and nearby Southern Ocean falls within the ice shelf stability zone (Fig. 12). Of note however, is that in 1850, the Antarctic Peninsula is only marginally contained within the stability zone.

Figure 12. Evolution of Arctic summer melting. Left: year 1850. Middle: year 2050. Right: year 2800. Yellow/dark red: ocean/land regions that experience more than 200 PDD/year. Turquoise/blue: ocean/land regions that do not experience more than 200 PDD/year. Red dots (overlapping): Ayles and Ward Hunt ice shelves.

The model showed that warming trends forced by fossil fuel CO_2 emissions result in simulated loss of the Ayles, Ward Hunt and any remaining ice shelves in the Arctic by around 2100.

Figure 13. Evolution of Antarctic summer melting. Left: year 1850. Middle: year 2050. Right: year 2800. Yellow/red: ocean/land regions that experience more than 200 PDD/year. Turquoise/blue: ocean/land regions that do not experience more than 200 PDD/year. Red dots: Larsen A/B and Wilkins ice shelves. Note that The Ross and Ronne-Filchener ice shelves are represented as ocean here, despite the fact that they exist as idealized ice shelves in the model.

The model has also demonstrated that the predicted southwards advancement of ice sheet stability zone along the Antarctic Peninsula (Fig. 13), which fits well with progressive break-up of the Larsen ice shelf in 2002 and Wilkins ice shelf in 2007/2008. The model shows that the ice sheet stability zone will continue to diminish in the future with the predicted increase in PDD for this region. In the absence of a mechanism that reinforces ice shelf stability, it is expected that increased summer melting in the future will degrade the strength of Antarctica's larger ice shelves with important implications for the WAIS and sea level rise.

NZ TEMPERATE GLACIERS

The ice mass in the New Zealand Southern Alps has reduced due to warming since the mid-19th century (Salinger et al., 1995), with estimates of the magnitude of loss varying between 30% (Ruddell, 1995) and 48% (Hoelzle et al., 2007). However, during the period of 1983-1997 there was a period of growth in glacier volume. More recently (1997 – present), the southern glaciers have oscillated between increasing and decreasing volume (See Fig. 14).

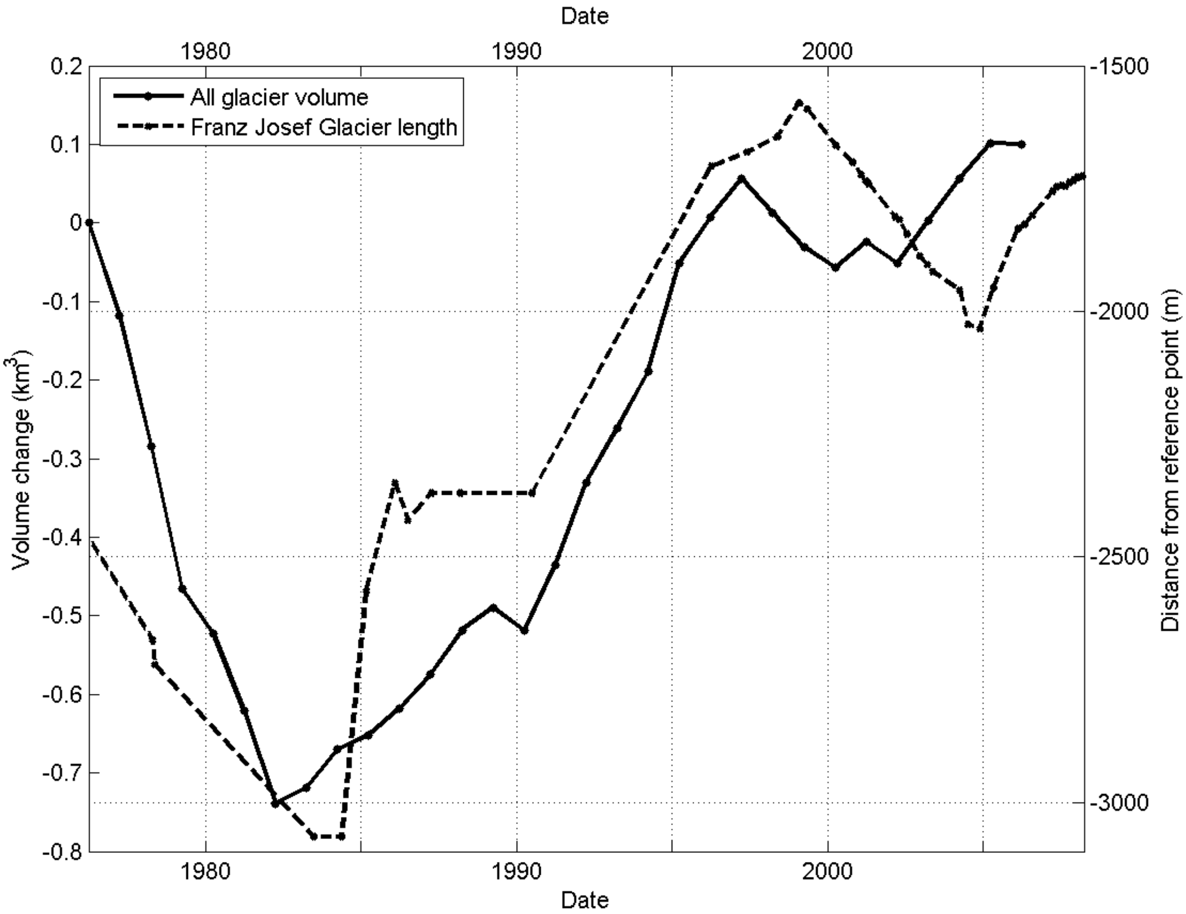


Figure 14. Ice mass balance comparing the Franz Josef glacier and all New Zealand glaciers (1975 – 2005).

The increase of volume since 1983 and the more recent fluctuations in volume have been occurring against a background of global climate change and 'globally' increasing temperatures. So how can the Southern Alps ice mass be increasing in a warming world?

The ANZICE modelling research into the Southern Alps glaciers concentrates on formulating models that relate regional climatic variables to mass balance. Mass balance is the amount of snow supplied to a glacier versus the loss of ice by melting. A regional energy balance model has been developed and applied successfully to assess changes in glacier volume between 1976 and 2006. This energy balance model has also assessed the gradients of mass balance sensitivity from west to east across the mountain range. That model is now being coupled to glacier flow model.

Important findings from this modelling include:

1. Temperature is the stronger driver of mass balance in the temperate glaciers of New Zealand.

2. The NZ glaciers are extremely sensitive to temperature changes.

3. Mass balance increases in recent times (since 1983) have resulted from regional cooling of 0.1°C. This regional cooling is consistent with a global warming trend that brings more frequent anti-cyclones to the Tasman Sea area, which draws cooler southerly air flows over the South Island. This fluctuating pattern of cold periods is superimposed on a general upward rise in global average temperature.

DRIVERS OF MASS BALANCE AND VOLUME CHANGE

Glaciers are inherently complex with many factors that control their length, speed and volume. ANZICE research derives volume changes directly from meteorological data. The advantage of this approach is that it provides an opportunity to tease out the strictly meteorological component of glacier forcing (as opposed to influences of glacier dynamics, rock debris cover, lake formation, etc) and to determine the drivers of volume change.

While this research focuses on the overall ice volume in the Southern Alps glaciers, two glaciers are used to characterise the kinds of glaciers that exist within the data set, and therefore the strength of the relationships between glaciers of different characteristics and the dominant meteorological driver. The Franz Josef and Brewster Glaciers are very different in terms of volume and altitudinal range. The Brewster Glacier has a very limited altitudinal range of around 500m whereas the Franz Joseph spans around 2460m. However, despite these differences models have shown that both are very sensitive to variations in temperature.

For the Brewster Glacier, figure 15 clearly demonstrates how the mass balance of the portion of the glacier below 2000m altitude responds to small changes in temperature .

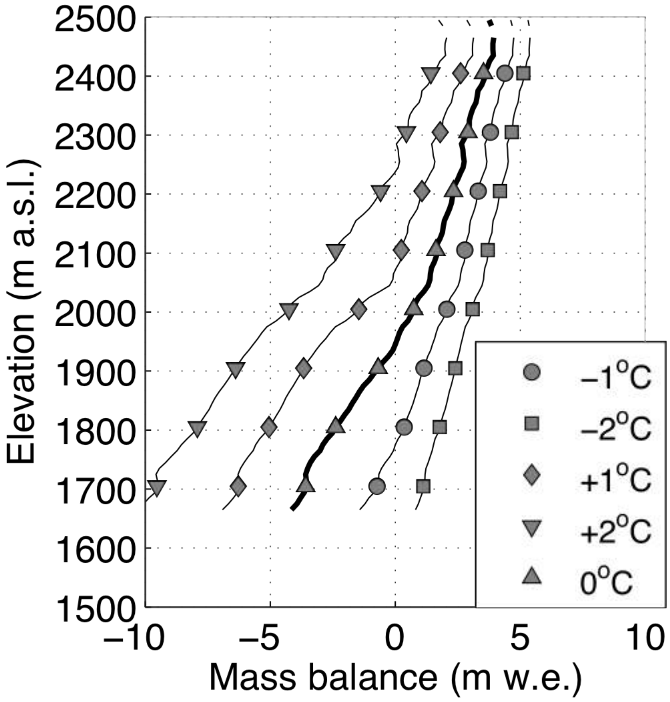


Figure 15. Brewster temperature-related mass balance changes (m w.e. or 'meters of water equivalent' is the measurement for reporting annual mass balance changes).

Run-off from the glacier confirms the glacier's extremely sensitivity to temperature changes. A 1°C increase in temperature leads to a 60% increase in runoff; conversely a 1°C decrease in temperature leads to a 20% decrease in runoff. The high sensitivity of runoff to warmer temperatures is also the result of feedbacks associated with albedo (ability of the surface to reflect sunlight i.e. high albedo reflects more sunlight) and turbulent fluxes. As temperature increases, higher turbulent heat fluxes lead to higher melting rates of snow cover, which leaves more of the glacier as exposed ice. Exposed ice absorbs more of the solar radiation than snow because of its lower albedo and the turbulent fluxes increase because the ice surface is rougher.

A popular tourist destination and often in the media, the Franz Josef Glacier terminus position tracks with the total ice volume closely, with a lag of 2-3 years. Sensitivity analyses indicate that ice volume is also sensitive to temperature, with a 40% increase in precipitation required to offset a 1°C warming.

Overall, the model showed that the relative sensitivities of mass balance to temperature and precipitation on central Southern Alps glaciers indicate that a 45% increase in precipitation is required to offset ice lost through a 1 °C warming.

El Niño weather patterns over New Zealand generate a south-westerly airflow which can result in higher precipitation, lower temperatures and increased cloudiness. It is known that such changes associated with ENSO influence glacier mass balance (Hooker and Fitzharris, 1999). The relatively small sensitivity of mass balance to precipitation changes identified in this research indicates that higher precipitation associated with El Niño conditions, is unlikely to be the dominant variable influencing recent mass balance trends. It is more likely that the reduced temperature and increased cloudiness dominate.

The Southern Alp ice mass provides important water storage capacity for the South Island hydro-electric power generation, summer irrigation for the drought prone East Coast as well as being an important tourist attraction. It is necessary to understand the implications of climate events such as El Niño and how projected climate change will impact on the Southern Alps ice mass. Should the long term trend observed since the 19th century (reduction in total ice mass) continue, this could lead to a decrease in summer run-off rates, with serious implications for the medium to long term management of New Zealand's hydro-electric power generation systems and primary production capabilities.

POLICY IMPLICATIONS

Our findings provide insight into the major drivers of recent mass balance changes on New Zealand glaciers. The fact that some New Zealand glaciers have recently advanced in a global climate that is warming can appear contradictory. In the instance of the Southern Alps glaciers, this research has demonstrated that the sensitivity to temperature is the dominant driver of glacial mass balance, which in turn leads to variations in terminus positions. Events such the El Niño – La Niña cycle can significantly alter the glacier mass balance in New Zealand and produce relatively short term changes in the context of an overall diminishing ice field.

On a global scale, this research confirms that most maritime glaciers are likely to be the most sensitive to a warming world, and will hence make a significant contribution to sea-level rise in the short to medium term. Glaciers in the high-precipitation environment of the western Southern Alps are extremely sensitive to temperature changes that drive a series of feedbacks (albedo, surface roughness etc.). The high sensitivity is likely to be regional and not only includes large glaciers such as Franz Josef Glacier, which show dramatic advance and retreat for relatively small climatic changes, but also smaller, less dynamic glaciers such as the Brewster Glacier.

Sensitivity of run-off to temperature rises will lead to significant short term increases in run-off in glaciated catchments. In the longer term, run-off will decrease as it is limited by the total ice volume in the Southern Alps.

New Zealand has a unique energy generation and economic profile. As a developed nation, it relies heavily on hydro-electric generation and agricultural exports. The Southern Alp ice mass provides naturally occurring water storage that is extremely important for these and other human activities. The impacts of climate change on the ice mass (a 30%-50% reduction over the last ~150 years), means that we are currently operating in an environment of water excess, and on average, year by year the ice mass storage capacity for future summers is being diminished. Ultimately, relatively small increases in temperature may lead to a reduction in electricity generation potential and increased drought vulnerability.

Policy Summary

Those responsible for making decisions concerning resource management and climate change policy, can only work confidently when they have reliable information. High quality science helps us understand natural processes and the consequences of human interventions in these processes. But even the highest quality science cannot fully eliminate uncertainty. Science can however, narrow the range of uncertainty and increase confidence in our understanding of complex systems, to the extent that we can make prudent decisions when considering:

a. The likely future impacts of climate change on society,
b. How we might adapt to those changes, and
c. How we might lower the future costs of adaptation through mitigating climate change where possible and practicable.

In order to lower our uncertainty concerning climate change in a New Zealand/Southern Ocean/Antarctic setting, we need to continue to build a solid foundation through rigorous and high quality research. This will enable New Zealand society to make resource management and infrastructural investment decisions with greater confidence and help to lower risks associated with these decisions.

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